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CITATION:

Weiss, G.S.. A Singular Limit arising in Combustion Theory : Identification of the Limit (Nonlinear Diffusive Systems : Dynamics and Asymptotics). 数理解析研究所講究録 2000, 1178: 29-35

ISSUE DATE:

2000-12

URL:

<http://hdl.handle.net/2433/64523>

RIGHT:

# A Singular Limit arising in Combustion Theory: Identification of the Limit

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This is an announcement of results to appear.

Let us consider the family of non-negative solutions for the initial-value problem

$$\partial_t u_\epsilon - \Delta u_\epsilon = -\beta_\epsilon(u_\epsilon) \text{ in } (0, \infty) \times \mathbf{R}^n, \quad u_\epsilon(0, \cdot) = u_\epsilon^0 \text{ in } \mathbf{R}^n. \quad (1)$$

Here  $\epsilon \in (0, 1)$ ,  $\beta_\epsilon(z) = \frac{1}{\epsilon} \beta(\frac{z}{\epsilon})$ ,  $\beta \in C_0^1([0, 1])$ ,  $\beta > 0$  in  $(0, 1)$  and  $\int \beta = \frac{1}{2}$ . We assume the initial data  $(u_\epsilon^0)_{\epsilon \in (0, 1)}$  to be bounded in  $C^{0,1}(\mathbf{R}^n)$  and to satisfy  $u_\epsilon^0 \rightarrow u^0$  in  $H^{1,2}(\mathbf{R}^n)$  and  $\bigcup_{\epsilon \in (0, 1)} \text{supp } u_\epsilon^0 \subset B_S(0)$  for some  $S < \infty$ .

Formally, each limit  $u$  with respect to a sequence  $\epsilon_m \rightarrow 0$  will be a solution of the free boundary problem

$$\partial_t u - \Delta u = 0 \text{ in } \{u > 0\} \cap (0, \infty) \times \mathbf{R}^n, \quad |\nabla u| = 1 \text{ on } \partial\{u > 0\} \cap (0, \infty) \times \mathbf{R}^n. \quad (2)$$

The singular limit problem (1) has been derived as a model for the propagation of equidiffusional premixed flames with high activation energy ([4]); here  $u = \lambda(T_c - T)$ ,  $T_c$  is the flame temperature, which is assumed to be constant,  $T$  is the temperature outside the flame and  $\lambda$  is a normalization

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\*Partially supported by a Grant-in-Aid for Scientific Research, Ministry of Education, Japan.

factor.

Let us shortly summarize the mathematical results directly relevant in this context, beginning with the limit problem (2): In the excellent paper [1], H.W. Alt and L.A. Caffarelli proved via minimization of the energy  $\int (|\nabla u|^2 + \chi_{\{u>0\}})$  – here  $\chi_{\{u>0\}}$  denotes the characteristic function of the set  $\{u > 0\}$  – existence of a stationary solution of (2) in the sense of distributions. They also derived regularity of the free boundary  $\partial\{u > 0\}$  up to a set of vanishing  $n - 1$ -dimensional Hausdorff measure. The question of the existence of classical solutions in three dimensions stands still exposed. Existence would however follow by [13], once the non-existence of singular minimizing cones has been established. *Non-minimizing* singular cones *do* in fact appear for  $n = 3$  (cf. [1, example 2.7]). Moreover it is known, that solutions of the Dirichlet problem in two space dimensions are not unique (cf. [1, example 2.6]).

For the time-dependent (2), a “trivial non-uniqueness” complicates the matter further, as the positive solution of the heat equation is always another solution of (2). Even for flawless initial data, classical solutions of (2) develop singularities after a finite time span; consider e.g. the example of two colliding traveling waves

$$\begin{aligned} u(t, x) = & \chi_{\{x+t>1\}}(\exp(x+t-1) - 1) \\ & + \chi_{\{-x+t>1\}}(\exp(-x+t-1) - 1) \text{ for } t \in [0, 1]. \end{aligned} \quad (3)$$

Let us now turn to results concerning the singular perturbation (1): For the stationary problem (1) H. Béréstycki, L.A. Caffarelli and L. Nirenberg obtained in [3] uniform estimates and – assuming the existence of a minimal solution – further results.

L.A. Caffarelli and J.L. Vazquez contributed in [8] among other things the corresponding uniform estimates for the time-dependent case and a convergence result: for initial data  $u^0$  that is strictly mean concave in the interior of its support, a sequence of  $\epsilon$ -solutions converges to a solution of (2) in the sense of distributions.

Let us finally mention several results on the corresponding two-phase problem, which are relevant as solutions of the one-phase problem are automatically solutions of the corresponding two-phase problem. In [6] and [7], L.A. Caffarelli, C. Lederman and N. Wolanski prove convergence to a sort of barrier solution in the case that  $\{u = 0\}^\circ = \emptyset$ . In [11], C. Lederman and N. Wolanski show convergence to a viscosity solution in the sense of [5] and derive regularity of the true two-phase part of the free boundary. These results deal quite well with the *true two-phase behavior* of limits, but have – as will become more plain in the examples below – to largely ignore the one-phase behavior. One of the reasons for this is that the limit cannot be expected to be close to a monotone function near free boundary points that are not true two-phase points.

Our result: As an intermediate result we obtain that each limit  $u$  of (1) is a solution *in the sense of domain variations*, i.e.  $u$  is smooth in  $\{u > 0\}$  and satisfies

$$\int_0^\infty \int_{\mathbf{R}^n} [-2\partial_t u \nabla u \cdot \xi + |\nabla u|^2 \operatorname{div} \xi - 2\nabla u D\xi \nabla u] = - \int_0^\infty \int_{R(t)} \xi \cdot \nu d\mathcal{H}^{n-1} dt \quad (4)$$

for every  $\xi \in C_0^{0,1}((0, \infty) \times \mathbf{R}^n; \mathbf{R}^n)$ . Here

$$R(t) := \{x \in \partial\{u(t) > 0\} : \text{there is } \nu(t, x) \in \partial B_1(0) \text{ such that } u_r(s, y) = \frac{u(t + r^2 s, x + ry)}{r} \rightarrow \max(-y \cdot \nu(t, x), 0) \text{ locally uniformly in } (s, y) \in \mathbf{R}^{n+1} \text{ as } r \rightarrow 0\}$$

is for a.e.  $t \in (0, \infty)$  a countably  $n-1$ -rectifiable subset of the free boundary. Let us remark that already this equation contains information (apart from the rectifiability of  $R(t)$ ) that cannot be inferred from the viscosity notion of solution [11, Definition 4.3]: whereas any function of the form  $\alpha \max(x_n, 0) + \beta \max(-x_n, 0)$  with  $\alpha, \beta \in (0, 1]$  is a viscosity solution in the sense of [11, Definition 4.3], positive  $\alpha$  and  $\beta$  have to be equal in order to satisfy (4).

Our main result is then that each limit of (1) – no additional assumptions are necessary – satisfies for a.e.  $t \in (0, \infty)$

$$\begin{aligned} \int_{\mathbf{R}^n} (\partial_t u(t) \phi + \nabla u(t) \cdot \nabla \phi) &= - \int_{R(t)} \phi d\mathcal{H}^{n-1} \\ &- \int_{\Sigma_*(t)} 2\theta(t, \cdot) \phi d\mathcal{H}^{n-1} - \int_{\Sigma_z(t)} \phi d\lambda(t) \end{aligned} \quad (5)$$

for every  $\phi \in C_0^1(\mathbf{R}^n)$ , that the non-degenerate singular set

$\Sigma_*(t) := \{x \in \partial\{u(t) > 0\} : \text{there is } \theta(t, x) \in (0, 1] \text{ and } \xi(t, x) \in \partial B_1(0) \text{ such}$

$$\begin{aligned} \text{that } u_r(s, y) = \frac{u(t + r^2 s, x + ry)}{r} &\rightarrow \theta(t, x) |y \cdot \xi(t, x)| \text{ locally uniformly} \\ &\text{in } (s, y) \in \mathbf{R}^{n+1} \text{ as } r \rightarrow 0\} \end{aligned}$$

is for a.e.  $t \in (0, \infty)$  a countably  $n-1$ -rectifiable subset of the free boundary whereas  $\lambda(t)$  is for a.e.  $t \in (0, \infty)$  a Borel measure such that the  $n-1$  dimensional Hausdorff measure is on

$$\Sigma_z(t) := \{x \in \partial\{u(t) > 0\} : r^{-n-2} \int_{Q_r(t, x)} |\nabla u|^2 \rightarrow 0 \text{ as } r \rightarrow 0\}$$

totally singular with respect to  $\lambda(t)$ , i.e.  $r^{1-n} \lambda(t)(B_r(x)) \rightarrow 0$  for  $\mathcal{H}^{n-1}$ -a.e.  $x \in \Sigma_z(t)$ . Up to a set of vanishing  $\mathcal{H}^{n-1}$  measure,  $\partial\{u(t) > 0\} = R(t) \cup \Sigma_*(t) \cup \Sigma_z(t)$ .

Let us shortly describe relevant parts of the proof:

As a first step, we prove convergence of  $2B_{\epsilon_m}(u_{\epsilon_m})$  to a characteristic function. We also need some control over the set of *horizontal points*, i.e. the set of points at which the solution's behaviour in the time direction is dominant. A crucial tool in the local analysis at the free boundary is the *monotonicity formula*

**Theorem 1 ( $\epsilon$ -Monotonicity Formula)** *Let  $(t_0, x_0) \in (0, \infty) \times \mathbf{R}^n$ ,  $T_r^-(t_0) = (t_0 - 4r^2, t_0 - r^2) \times \mathbf{R}^n$ ,  $0 < \rho < \sigma < \frac{\sqrt{t_0}}{2}$  and*

$$G_{(t_0, x_0)}(t, x) = 4\pi(t_0 - t) |4\pi(t_0 - t)|^{-\frac{n}{2}-1} \exp\left(-\frac{|x - x_0|^2}{4(t_0 - t)}\right).$$

Then

$$\begin{aligned} \Psi_{(t_0, x_0)}^\epsilon(r) &= r^{-2} \int_{T_r^-(t_0)} \left( |\nabla u_\epsilon|^2 + 2B_\epsilon(u_\epsilon) \right) G_{(t_0, x_0)} + \\ &\quad - \frac{1}{2} r^{-2} \int_{T_r^-(t_0)} \frac{1}{t_0 - t} u_\epsilon^2 G_{(t_0, x_0)} \end{aligned}$$

satisfies the monotonicity formula

$$\begin{aligned} \Psi_{(t_0, x_0)}^\epsilon(\sigma) - \Psi_{(t_0, x_0)}^\epsilon(\rho) &\geq \int_\rho^\sigma r^{-1-2} \int_{T_r^-(t_0)} \frac{1}{t_0 - t} \left( \nabla u_\epsilon \cdot (x - x_0) \right. \\ &\quad \left. - 2(t_0 - t) \partial_t u_\epsilon - u_\epsilon \right)^2 G_{(t_0, x_0)} dr \geq 0 . \end{aligned}$$

The key to our result is then an *estimate for the parabolic mean frequency*.

**Proposition 1** *On the closed set  $\Sigma := \{(t, x) \in (0, \infty) \times \mathbf{R}^n : \Psi_{(t, x)}(0+) = 2H_n\}$  the parabolic mean frequency*

$$2 \left( \int_{T_r^-(t)} \frac{1}{t-s} u^2 G_{(t, x)} \right)^{-1} \int_{T_r^-(t)} |\nabla u|^2 G_{(t, x)} \geq 1 .$$

*The function  $r \mapsto r^{-2} \int_{T_r^-(t)} \frac{1}{t-s} u^2 G_{(t, x)}$  is non-decreasing and has a right limit  $\theta^2(t, x) \int_{T_1^-(0)} \frac{1}{-s} |x_1|^2 G_{(0, 0)}$ . The function  $\theta$  is upper semicontinuous on  $\Sigma$ . At each  $(t, x) \in \Sigma$*

$$\int_0^r s^{-3} \int_{T_s^-(t)} (1 - \chi) G_{(t, x)} ds \rightarrow 0 \text{ as } r \rightarrow 0 .$$

It is a surprising fact that the parabolic mean frequency is bounded from below at each point of highest density, which includes the set  $\Sigma_\star$ . As a consequence we obtain *unique tangent cones* for a.e. time and at  $\mathcal{H}^{n-1}$ -a.e. point of the graph of  $u$ , whence GMT-tools lead to our result.

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